A **Spherical Ballute** (upper) **and a Lens-Shaped Ballute** (lower) have been considered for inflatable emergency atmospheric-entry vehicles.

space shuttle. In contrast, an inflatable emergency-landing vehicle according to the proposal would have a mass between 100 and 200 kg, could be stored in a volume of approximately 0.2 to 0.4 m³, and could likely be designed and built much less expensively.

When fully inflated, the escape vehicle behaves as a large balloon parachute, or ballute. Due to very low mass-per-surface area, a large radius, and a large coefficient of drag, ballutes decelerate at much higher altitudes and with much lower heating rates than the space shuttle. Although the space shuttle atmospheric reentry results in surface temperatures of about 1,600 $^{\circ}$C, ballutes can be designed for maximum temperatures below 600 $^{\circ}$C. This allows ballutes to be fabricated with lightweight ZYLON$^{\circledR}$, or polybenzoxazole (PBO), or equivalent.

Two preliminary cocoon ballute "lifeboat" concepts are shown in the figures. The cocoon portion of the vehicle would be, more specifically, a capsule pressurized to 1 bar (0.1 MPa — approximately 1 standard atmosphere). Crewmembers would enter the cocoon pod and then zip it shut. The spacecraft would be placed on a reentry trajectory, and the inflated cocoon with deflated ballute would be ejected.

Once the vehicle was safely away from the spacecraft, the entire ballute would be inflated. For this inflation at high altitude, the ballute would be pressurized to about 0.01 bar (1 kPa). As low as this pressure is, it is at least ten times the expected dynamic pressure on the vehicle during the heating portion of very high atmospheric reentry, and hence it is sufficient to enable the ballute to retain its shape. From thermal reentry heating analyses performed at JPL, the diameter of the inflated ballute would be made large enough (30 to 40 m) to limit the maximum temperature to about 500 $^{\circ}$C — safely below the 600 $^{\circ}$C limit for PBO, or equivalent.

The spherical ballute shown in the upper figure would have a mass of about 200 kg for a seven-astronaut rescue mission, while the lens-shaped ballute in the lower figure has been further improved by reducing the overall mass required and increasing the coefficient of drag. To maintain stability, the center of mass of both concepts must be kept low, and spin stabilization may be necessary.

Lightweight Deployable Mirrors With Tensegrity Supports
Extremely lightweight, deployable structures could be made by assembling tensegrity modules.

Marshall Space Flight Center, Alabama

The upper part of Figure 1 shows a small-scale prototype of a developmental class of lightweight, deployable structures that would support panels in precise alignments. In this case, the panel is hexagonal and supports disks that represent segments of a primary mirror of a large telescope. The lower part of Figure 1 shows a complete conceptual structure containing multiple hexagonal panels that hold mirror segments.

The structures of this class are of the tensegrity type, which was invented five decades ago by artist Kenneth Snelson. A tensegrity structure consists of moment-free compression members (struts) and tension members (cables). The structures of this particular developmental class are intended primarily as means to erect large segmented primary mirrors of astronomical telescopes or large radio antennas in outer space. Other classes of tensegrity structures could also be designed for terrestrial use as towers, masts, and supports for general structural panels.

An important product of the present development effort is the engineering practice of building a lightweight, deployable structure as an assembly of tensegrity modules like the one shown in Figure 2. This module comprises two octahedral tensegrity subunits that are mirror images of each other joined at their plane of mirror symmetry. In this case, the plane of mirror symmetry is both the upper plane of the lower subunit and the lower plane of the upper subunit, and is delineated by the midheight triangle in Figure 2. In the configuration assumed by the module to balance static forces under mild loading, the upper and lower planes of each sub-

Figure 1. A **Tensegrity Structure** supports a lightweight, thermally formed, hexagonal plastic panel that, in turn, supports silicon disks that represent segments of an astronomical mirror. A fully developed version would comprise a hexagonal array of multiple hexagonal panels on a supporting tensegrity structure.

Figure 2. This **Tensegrity Module** comprises two subunits that, together, undergo zero net rotation (to first order) under a longitudinal (vertical in this view) load.

unit are rotated about 30°, relative to each other, about the long (vertical) axis of the structure. Larger structures can be assembled by joining multiple modules like this one at their sides or ends.

When the module is compressed axially (vertically), the first-order effect is an increase in the rotation angle, but by virtue of the mirror arrangement, the net first-order rotation between the uppermost and lowermost planes is zero. The need to have zero net rotation between these planes under all loading conditions in a typical practical structure is what prompts the use of the mirror configuration. Force and moment loadings other than simple axial compression produce only second-order deformations through strains in the struts and cables.

Simple algebraic expressions have been derived to describe the deformations, under load, of multimodule platelike and mast structures, thereby making it possible to design such structures without need for computers. Perhaps the most important rules for designing a tensegrity structure are that (1) the lengths of the struts and cables are critical and they determine the unloaded shape of the structure, but that (2) the preloads (discussed in the next paragraph) in the cables and struts determine the degree of rigidity under external load.

To make a module stowable, it is necessary to provide for disconnection of the ends of many of the struts and/or make the struts collapsible (e.g., telescoping). To make a module deployable, one must provide means to reconnect the struts if disconnected and re-extend them if collapsed. The means of deployment must include means to apply the required preloads to the cables and struts. In cases of manual stowage and deployment, such means can include toggles and turnbuckles. For automated deployment, more sophisticated means are needed. In the structure of Figure 2, the struts are telescoping piston/cylinder units that are extended pneumatically and locked at full extension by spring-loaded mechanisms.